Continuous wave operation of Nd:$CaYAlO_4$ and Nd:$ScYSiO_5$ lasers with hot band diode-pumping

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ABSTRACT

Nd:SYSO and Nd:CALYO lasers were demonstrated with hot band pumping at 914 nm for the first time. The output power achieved was 201 mW centered at 1078.0 nm with slope efficiency of 18.6% for Nd:SYSO and 154 mW output centered at 1074.9 nm with 8.6% slope efficiency for Nd:CALYO. This pumping approach could offer further power scaling possibility due to the strongly reduced quantum defect and consequently lower thermal lensing.

Keywords: Diode-pumped lasers, Neodymium lasers, Solid-state lasers

1. INTRODUCTION

Neodymium-ion doped laser gain media have been extensively studied due to their high power capabilities and efficiency. Recently, several studies have focused on diode-pumping of neodymium lasers at absorption lines with longer wavelengths such as, for example, 880 nm, 888 nm and 914 nm in Nd:YVO_4 [1-10]. Utilizing these longer pumping wavelengths decreases the quantum defect (QD) which is defined as $QD = h\nu_{pump} - h\nu_{laser}$ and provides multiple advantages over traditional pump wavelength at the strongest absorption line around 810 nm.

First, the reduction of quantum defect translates directly into the lower amount of heat being generated inside the laser gain medium at the same amount of the absorbed power. This can help to significantly decrease thermal effects in the gain medium [11] and improves the stability of a laser cavity which in turn helps maintain the output beam quality and the optical efficiency. Moreover, the reduction of QD also allows for further power scaling which is particularly advantageous for laser gain media with disordered structures such as Nd:Glass or in our case, Nd:$CaYAlO_4$ (Nd:CALYO) and Nd:$ScYSiO_5$ (Nd:SYSO), since they are generally constrained by poor thermal conductivity (κ).

Secondly, from the relationship of slope efficiency described as

$$\eta = \frac{-\ln(1-T)}{-\ln(1-T)+L_i} \times \frac{\lambda_{Pump}}{\lambda_{Laser}}, \tag{1}$$

where η is the slope efficiency, T is the transmission of the output coupler (OC), L_i is the internal cavity loss, λ_{Pump} is the pump wavelength, and λ_{Laser} is the laser wavelength, the upper limit of slope efficiency of the laser system is determined by the ratio of the pump and laser wavelengths. This means that by decreasing the QD, the slope efficiency can be increased.

Thirdly, the laser diodes operating approximately at 910 nm (InGaAs) (and which can be used as low quantum defect pump sources for neodymium lasers) are currently being widely used as pump sources for Yb-doped fiber lasers. These laser diodes offer better lifetime, efficiency, and higher output power than their AlGaAs counterparts that generate 808, 880, and 888 nm output [5]. The beam quality of the fiber-coupled laser diodes at 914 nm is also more than 4 times better than that of AlGaAs laser diodes and therefore allows for better mode-matching in longer laser crystals with smaller absorption coefficient.

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The crystals of Nd:CALYO and Nd:SYSO exhibit strong inhomogeneous broadening of the emission spectra which are caused by multiple occupancy sites of the Nd-ion. Their thermo-optical properties are somewhat similar to the KGW crystal which is a well know host for Nd- and Yb-ions [9, 10, 12-17]. Broad emission spectra of Nd:CALYO and Nd:SYSO have strong potential for generation of ultrashort pulses which are widely used in nonlinear frequency conversion [18-21], nonlinear microscopy [22,23], and ultrafast spectroscopy [24,25]. Therefore, investigation of pumping approaches that offer power scaling of Nd:CALYO and Nd:SYSO lasers is very important.

1.1 Nd:$CaYAlO_4$ (Nd:CALYO)

Nd:CALYO crystal was first proposed as a new candidate for disordered structure laser crystal in 1977 by E. F. Kustov et al. [26] where the absorption and emission spectra of single crystals Nd:CALYO were initially reported. H. R. Verdún and L. M. Thomas later reported the first laser operation with Nd:CALYO pumped by GaAlAs diode laser array [27] in 1990.

Nd:CALYO was the first laser crystal discovered that is isostructural with reported tetragonal K_2NiF_4 structure where the Ca^{2+}, Y^{3+}, and Nd^{3+} can randomly occupy the same crystallographic site. This random distribution of different species creates the same effect as disordered crystals. The main reason for interest in Nd:CALYO is because of this disordered nature which translates to optical properties as seen in Nd:Glass, Nd:CNGG, and Nd:CLNGG such as smooth inhomogeneous broadening of absorption and emission spectral lines while still retaining the thermal properties closer to the other ordered structure crystals such as Nd:YVO_4. This inhomogeneous broadening of the emission spectrum ultimately will allow for generation of shorter pulses.

The absorption spectra of the uniaxial Nd:CALYO are shown in Fig. 1(a) and was measured by D. Z. Li et al. [28]. The typical pump band of interest is at 805 nm because of the availability of the generally employed AlGaAs pump diodes. The spectra also show small absorption for both polarizations for wavelengths longer than 900 nm.

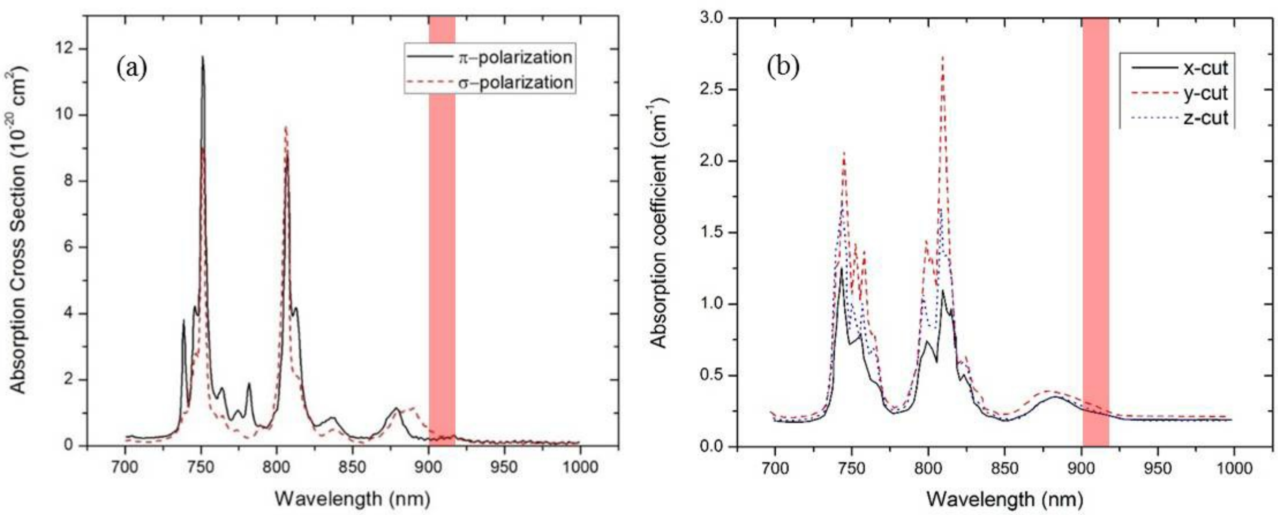

Figure 1. (a) Polarized absorption spectra of Nd:CALYO [28] (b) and of Nd:SYSO [31]. Colored areas (red) represent the wavelengths available from the laser diode module used in the described experiments.

1.2 Nd:$ScYSiO_5$ (Nd:SYSO)

Nd:SYSO is a newer crystal and was first demonstrated in CW and Q-switch regimes by S. D. Liu et al. [29], and in passive mode-locking by V. Aleksandrov et al. [30]. The absorption cross-sections for different cuts of Nd:SYSO as given by S. D. Liu et al. are shown in Fig. 1(b) [31]. Similar to Nd:CALYO, there is small absorption for the wavelengths longer than 900 nm.

Table 1 shows the comparison of some of the important optical and mechanical properties of the studied crystals with Nd:YVO_4 all of which are suitable for medium range output power.

Table 1. Comparison optical and mechanical properties of $Nd:YVO_4$, Nd:CALYO, and Nd:SYSO

Laser Crystal	λ_{em} (nm)	σ_{em} (10^{-20} cm^2)	$\Delta\lambda$ (nm)	κ ($Wm^{-1}K^{-1}$)	α ($10^{-6}K^{-1}$)	*dn/dT* ($10^{-6}K^{-1}$)	τ (μs)	Ref.
$Nd:YVO_4$	1064	141 (π)	0.96	∥C 5.23 ⊥C 5.10	α_a 4.43 α_c 11.37	n_o 8.5 n_e 3.0	90	[32,33]
Nd:CALYO	1080	10.44 (σ)	15	∥C 3.2 ⊥C 3.6	α_a 8 α_c 11	n_o 8.5 n_e 12	114	[26,28]
Nd:SYSO	1075.6	9.92	15.4	-	-	-	-	[31]

As can be seen from table 1, both Nd:CALYO and Nd:SYSO have clear advantage over $Nd:YVO_4$ in terms of emission bandwidth which offers the possibility of sub-picosecond pulse generation while trading away some of the thermal properties as is in the case of Nd:CALYO.

In this report, we demonstrate for the first time low quantum defect pumping at 914 nm of these two gain media with disordered structure, Nd:CALYO and Nd:SYSO, in order to minimize thermal lensing effects and offer a route to further power scaling.

2. EXPERIMENTAL SETUP

A 20 mm-long Nd:CALYO crystal was used in a 3-mirror cavity as shown in Fig. 2. The crystal was pumped by a fiber-coupled diode laser with a fiber core diameter of 105 µm and a numerical aperture of 0.15. The maximum pump power was limited to 24.3 W. The pump was then coupled into the crystal with a set of achromatic doublet with 40 mm focal length and 150 mm focal length. The spot size diameter of the pump beam at the center of the gain medium was ~400 µm.

The crystal was wrapped in an indium foil and water cooled at 16 °C at the flow rate of 1 liter/minute on the top and bottom surfaces by a copper holder. The gain medium was in-band pumped at 914 nm at the highest pump power level. Both surfaces of the crystal were anti-reflection coated. However, the one-pass loss through the crystal was measured to be ~9% at 1064.1 nm which was attributed to the relatively low crystal quality. M3 was a dichroic mirror with high reflection at 1080 nm (T > 99.5%). Output couplers (OC) with 1.6-5% transmission in the 1040-1090 nm range were used in the experiment in order to determine the highest output power and optical efficiency.

Two 5 mm-long 0.8 at.% doped Nd:SYSO crystals with anti-reflection coatings were put back-to-back and used in a similar 3-mirror cavity setup. The optimum output coupler in this case was found to be 1.6%.

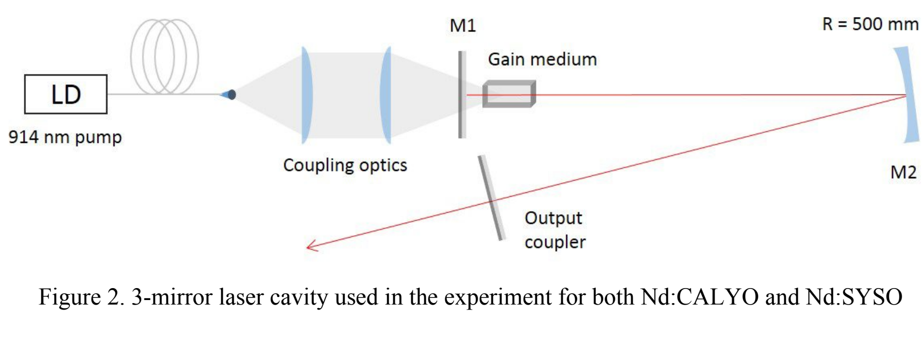

Figure 2. 3-mirror laser cavity used in the experiment for both Nd:CALYO and Nd:SYSO

3. RESULTS AND DISCUSSIONS

The absorbed pump power was 8.2 W and 3.3 W for Nd:CALYO and Nd:SYSO, respectively. Fig. 3 shows the absorbed pump power versus the incident laser diode power. The experimental results were limited by the low pump absorption in the crystals which could be increased further by higher doping concentration, using a longer crystal (in the case of Nd:SYSO), or utilizing multiple pass geometry. Regarding the available pump power, high-power fiber-coupled laser diodes around 914 nm (>100 W) are widely used for pumping of Yb-doped fiber lasers and are readily available for further power scaling experiments.

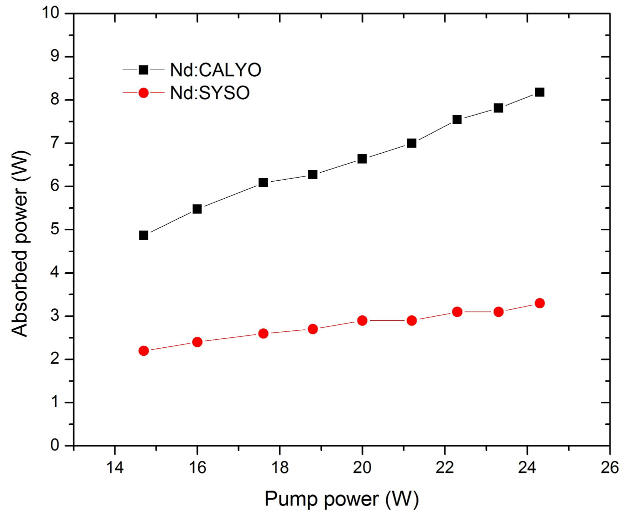

Figure 3. The absorbed power versus the available pump power for Nd:CALYO and Nd:SYSO.

The output powers achieved were 201 mW for the Nd:SYSO and 154 mW for the Nd:CALYO. Fig. 4 shows the measured output power for both crystals. The highest slope efficiency for Nd:SYSO laser was found to be 18.6% while the slope efficiency for Nd:CALYO was 8.6%. The low slope efficiency and output power in Nd:CALYO case are likely due to the fact that the crystal had very high losses at the laser wavelength caused by poor optical quality.

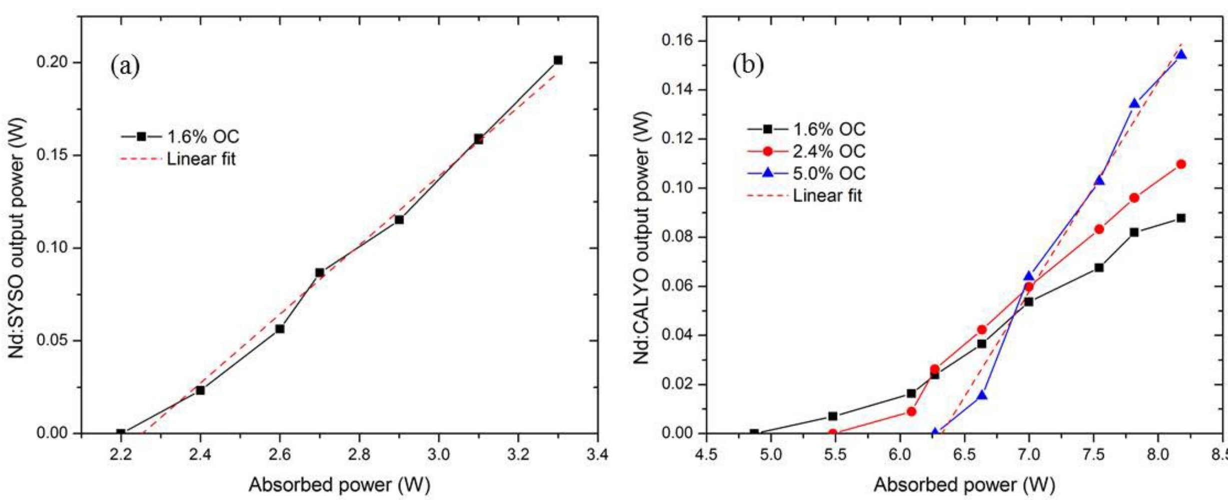

Figure 4. (a) The output power versus the absorbed pump power for Nd:SYSO; (b) The output power versus the absorbed pump power for Nd:CALYO with various values of output coupler transmission.

The laser spectra are shown in Fig. 5. The central wavelengths were 1079.8 for the Nd:CALYO and 1074.9 nm for the Nd:SYSO. The FWHM of the spectra were 0.14 nm and 0.17 nm, respectively.

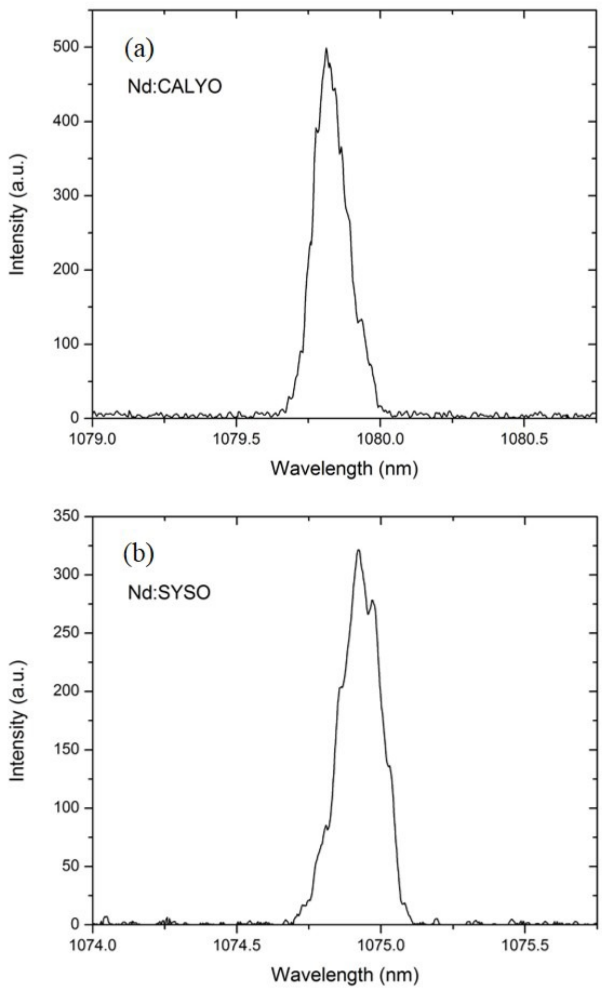

Figure 5. Laser spectra of (a) Nd:CALYO and (b) Nd:SYSO.

4. CONCLUSIONS

In summary, two neodymium lasers with disordered structure gain media, Nd:SYSO and Nd:CALYO, were demonstrated with hot band pumping at 914 nm for the first time in order to decrease the quantum defect which plays a large roll in fractional thermal loading. The maximum output powers achieved were 201 mW centered at 1074.9 nm with slope efficiency of 18.6% for Nd:SYSO and 154 mW centered at 1079.8 nm with 8.6% slope efficiency for Nd:CALYO. This pumping approach offers further power scaling possibility due to the availability of powerful InGaAs laser diodes around 910 nm, the strongly reduced quantum defect, and consequently thermal lensing. Our future work will concentrate on studying thermal effects in these gain media by using a modified beam propagation technique [34], performance with different cuts [35] as well as possible dual-wavelength operation [36-38].

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